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WEIGHTLESSNESS EXPERIMENTS WITH LIQUID HYDROGEN IN AEROBEE SOUNDING ROCKETS; UNIFORM RADIANT HEAT ADDITION - FLIGHT 3 (U)

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WEIGHTLESSNESS EXPERIMENTS WITH LIQUID HYDROGEN IN AEROBEE SOUNDING ROCKETS; UNIFORM RADIANT HEAT ADDITION - FLIGHT 3*

By Robert R. Nunamaker, Elias L. Corpas,
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SUMMARY

As part of a broad study of the effects of weightlessness on the handling of fluids, Aerobee-launched heat-transfer experiments with liquid hydrogen have been performed. With the Aerobee sounding rocket, it was possible to obtain about 4 minutes of nearly zero gravity with a 300-pound experiment containing a 9-inch-diameter liquid-hydrogen storage vessel. For the third Aerobee firing, the cryogenic tank was 34-percent filled with liquid hydrogen and was uniformly heated by an average heat flux of 150 Btu per hour per square foot. Within a few seconds after rocket burnout, the liquid hydrogen completely wetted the container wall, which was then close to the saturation temperature. The wall temperatures gradually increased for about 150 seconds as the pressure and, thus, the saturation temperature of the liquid hydrogen within the closed container, reflected the radiant-heat addition. At 210 seconds after launch (158 sec after rocket burnout), a rapid increase in the wall temperature at the top of the vessel indicated the inception of wall drying. The wall drying spread during an additional 100 seconds of weightlessness until the upper hemisphere was vapor wetted and the lower hemisphere was liquid wetted. A considerable temperature gradient existed within the liquid, as evidenced by the excessive pressure rise of the sealed container compared with the pressure increase calculated on the basis of thermal equilibrium.

INTRODUCTION

The relatively high specific impulse available with liquid hydrogen as a rocket fuel makes this cryogenic fluid very desirable for space applications. The low storage temperature of liquid hydrogen results in a heating problem in space, which has received much attention in the literature. An equally important problem area that has yet to be thoroughly explored is the weightless characteristics of the liquid in a space environment. It would be desirable then to observe this fluid in a storage vessel under simultaneous action of heat transfer, surface tension, and inertial forces. To accomplish such an objective, the Aerobee zero-gravity program is being conducted by the staff of the Lewis Research Center. It should be pointed out that the applied experiments represented by the

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Aerobee tests are only part of the broad continuing research study of the characteristics of liquid hydrogen reviewed in reference 1. Essentially, the Aerobee sounding rocket is used to boost a 9-inch-diameter spherical hydrogen storage vessel into a ballistic trajectory with an apogee of about 80 nautical miles; this results in an effective weightless time of nearly 4 minutes. Variables to be studied will include both uniform and nonuniform heating at flux levels between 1 and 260 Btu per hour per square foot, liquid positioning with capillary control, fluid collection and venting, vessel filling, and others. Pressure, temperature, and photographic observations have been made during these zero-gravity experiments. The following table summarizes the test conditions of the first three Aerobee liquid-hydrogen experiments aboard Aerobee flights:

Flight	Liquid-hydrogen volume, percent	Uniform radiant heating, Btu/(hr)(sq ft)	Gravity level, g's	Report
1	22	260	±0.005	Ref. 2
2	32	150	0 to 2	Ref. 3
3	34.3	150	0.001	Present report

The object of this paper is to present the thermodynamic data from the third flight.

APPARATUS AND PROCEDURE

An Aerobee 150A sounding rocket was used to boost the heat-transfer experiment into a ballistic trajectory with an apogee of 81.5 nautical miles and a resultant weightless test time of about 200 seconds. The flight path is shown as a function of time in figure 1 with system operating sequences denoted. All systems of the flight experiment operated normally except the light source for the camera, its failure precluding a photographic record of the fluid condition. The collection operation 309 seconds after launch signaled the vent operation of the residual pressure in the fuel tank through two small nozzles that collected the liquid hydrogen at the bottom of the spherical container. Further details of the operational procedure are documented in references 2 and 3. A sketch of the vehicle and of the payload section, showing the major components, is presented in figure 2. A cross-sectional drawing of the experiment showing the 9-inch-diameter inner-sphere vessel, the heater sphere, the 11-inch-diameter nitrogen cooling jacket, and other parts is presented in figure 3. The liquid-vapor instruments shown inside the inner sphere were installed to evaluate their ability to sense the state of the fluid; the surface-tension force of liquid hydrogen caused the fluid to remain suspended within the sensor structure, and thus this device did not work properly. Location of the temperature instrumentation is shown in figure 4. Temperature transducers were attached to the outside skin of the 0.010-inch-thick stainless-steel hydrogen inner-sphere vessel, as pictured in figure 3. The thin inner-sphere wall and the fast-acting platinum resistance

temperature transducers resulted in temperatures closely reflecting the hydrogen state adjacent to the inner wall. A photograph of the interior of the liquid-hydrogen sphere prior to launch is shown in figure 5. The darker circle outlines the liquid hydrogen at the bottom of the container. A small glass sphere in the upper right portion of the picture was 40-percent filled with dyed ethyl alcohol and was used as an overall rough visual check of the acceleration environment.

The data-reduction procedure is detailed in reference 2.

RESULTS AND DISCUSSION

At the time of launch, the 9-inch-diameter spherical heat-transfer vessel was 34.3-volume-percent filled with liquid hydrogen. A uniform heat flux of about 150 Btu per hour per square foot was the desired heating level, to correspond to a bare stainless-steel tank exposed to the sun's radiation in a low Earth orbit. The first and second flights in this series of experiments are reported in references 2 and 3, respectively.

Traces showing both the lateral- and longitudinal-acceleration histories during the nearly weightless portion of the flight are presented in figure 6. During the coast period (about 100 to 300 sec after launch) the accelerometers registered less than 0.002 g. All pressure and temperature measurements taken during the flight were telemetered back to the launch site. Because of failure of the light source, shown in figure 3, a photographic record of the sphere's interior was not obtained. Although the longitudinal acceleration trace did not fall below 0.002 g until about 110 seconds after launch, the low gravity level immediately after booster cutoff at 52 seconds (below ±0.012 g) constituted the beginning of the weightless period for the purposes of this experiment.

Temperature traces of the upper and lower heater hemispheres are presented in figure 7 as a function of time. The desired flux level was 150 Btu per hour per square foot, which corresponded to a heater temperature of about 580° R. Although the heater was turned on about 40 seconds after launch (fig. 1), an additional 70 seconds were required to reach the desired flux level. The resultant net heat-transfer rate into the liquid hydrogen, including the system heat leaks, is shown in figure 8(a). It is important to realize that the storage-vessel heat leaks were a significant fraction of the total heat transfer at the low flux levels; these heat leaks are discussed in detail in reference 2. Near the rated heat-transfer level (100 sec after launch) the heat leakage is insignificant. The cumulative heat absorbed by the liquid hydrogen as a function of flight time is shown in figure 8(b).

Wall temperatures that were measured at 19 stations on the 9-inch-diameter vessel are shown as a function of time in figure 9 for the upper and lower hemispheres. Prior to launch, the liquid hydrogen at the bottom of the vessel was at a temperature of 37° R, which is the saturation temperature corresponding to the atmospheric pressure. The wall temperature above the liquid-vapor interface then increased in an orderly fashion up to 115° R near the thrust axis at the top of the vessel. Such a temperature distribution in a cryogenic storage vessel would be expected in a 1-g field, as explained in reference 4. Following launch, all the wall temperatures exposed to the gaseous hydrogen increased, but the thermal

stratification level apparent in the vapor at the 1-g condition was maintained. The rise in temperature of the vapor-wetted wall during boost phase when the total heat transfer was quite small (see fig. 8(b)) was due to the low heat capacity and removal rate of the gas adjacent to the thin steel container wall (0.010-in. thick). Soon after rocket burnout (52 sec), all the wall temperatures fell quickly toward the saturation liquid temperature, as the vapor ullage moved toward the central area and all the walls on the upper hemisphere were liquid wetted (fig. 9(a)). For the entire flight, the wall temperatures in the lower hemisphere corresponded to the slowly rising saturation temperature of this continuously liquid-wetted portion of the sphere. The rise in saturation temperature with increasing flight time simply reflected the pressure rise in a sealed storage vessel with steady heat input. The wall temperatures of the upper hemisphere (fig. 9(a)) indicate that, from about 60 to 210 seconds after launch, the walls were liquid wetted and also showed the slowly rising saturation liquid temperature. Suddenly at 210 seconds, however, temperature transducer 18, located $2\frac{1}{4}$ inches from the top thrust axis along the surface, indicated that the wall temperature rose rapidly above the saturation value, which meant that the container wall in the vicinity of this measurement was vapor wetted. Because the vapor could not dissipate the radiant heat input, the temperature of the vessel wall must rise. Following the first indication of wall drying at 210 seconds, there was progressive drying of the vessel walls spreading down toward the lower hemisphere; 280 seconds after launch, the wall drying had reached the vicinity of the container equator with respect to the thrust axis. The zero-gravity time for the vessel walls to dry is plotted as a function of distance from the thrust axis at the top of the container in figure 10. The orderly correlation of the temperature measurements on the upper hemisphere indicates the nearly symmetrical drying pattern with the inception near the top of the vessel. Although the inception point may have been caused by a concentrated heat flux at the camera port (located on the thrust axis, see fig. 3), such a heat leak was not shown to be a prerequisite for the drying by the analysis in reference 1. Unplanned wall drying of a cryogenic storage vessel can have important implications with respect to venting requirements, system pressure changes, and heat transfer considerations.

The measured pressure rise of the 9-inch-diameter storage vessel is shown as a function of time in figure 11. In addition, the calculated pressure rise, based on thermal equilibrium within the liquid, is indicated in the figure. The calculated and measured pressure rise agreed closely until 100 seconds after launch, when the measured pressure increased considerably faster than that calculated for thermal equilibrium. At 270 seconds after launch, for example, the calculated vessel pressure was 60 pounds per square inch and the measured pressure was 78 pounds per square inch. This 30-percent pressure differential becomes particularly important when it is realized that thermodynamic calculations for a cryogenic storage system in a weightless environment are generally based on thermal equilibrium (refs. 5 and 6). It was reasoned, then, that a thermal stratification must have been set up in the liquid hydrogen as it was heated in a closed vessel with a weightless environment. In a subsequent Aerobee experiment, where a temperature survey rake was installed near the wall, a 1° R temperature profile was measured in the liquid after 100 seconds of weightlessness (ref. 1).

At rocket burnout, there was a momentary 1-pound-per-square-inch-absolute rise in measured pressure (fig. 11) as the liquid suddenly sloshed against the hot container wall. As the fluid phases mixed between 52 and 60 seconds after launch, however, the measured pressure returned to the calculated equilibrium line. Firing of the small collection rockets at 310 seconds also caused a higher rate of pressure increase as the thermal stratification was eliminated, and the cold liquid slowly sloshed against the hot, dry container wall. This process continued for 40 seconds until separation at 350 seconds after launch, at which time the vessel pressure started to fall toward the thermal equilibrium line. Although about half the vessel was dry at both burnout (52 sec) and fluid collection (310 sec), the higher dry wall temperatures (see fig. 9(a)) and the slower mixing rate probably contributed to the marked pressure rise following fluid collection.

SUMMARY OF RESULTS

An Aerobee sounding rocket was used to boost a 9-inch-diameter liquid-hydrogen storage vessel into a ballistic trajectory that provided a nearly weightless test period of about 4 minutes. The average radiant-heat flux was 150 Btu per hour per square foot, with the storage vessel 34-percent filled with liquid hydrogen. Pressure and temperature measurements were telemetered continuously to the ground receiver station. Immediately following burnout of the booster rocket, the liquid hydrogen wetted the container walls, which were close to the saturation temperature of liquid hydrogen. Gradual heating of the closed vessel resulted in a steady rise in container pressure and wall temperatures. After about 150 seconds of weightlessness, the vessel started to dry at the top, and the process continued until the upper hemisphere was dry after 250 seconds of weightlessness. Because the measured vessel pressure rise was in excess of that calculated on the basis of thermal equilibrium, it was assumed that a temperature stratification existed in the liquid. A temperature rake installed near the wall in a subsequent test corroborated this assumption. Sloshing of the liquid against the hot, dry wall of the upper hemisphere resulted in a considerable vessel pressure rise as the liquid "flashed" into vapor. After sufficient mixing, the vessel pressure dropped toward the thermal equilibrium value. Phenomena observed during the Aerobee weightless experiments, such as wall drying, thermal stratification, and sloshing pressure rise, could have considerable effect on the storage of cryogenic fluids in a weightless environment.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, July 25, 1963

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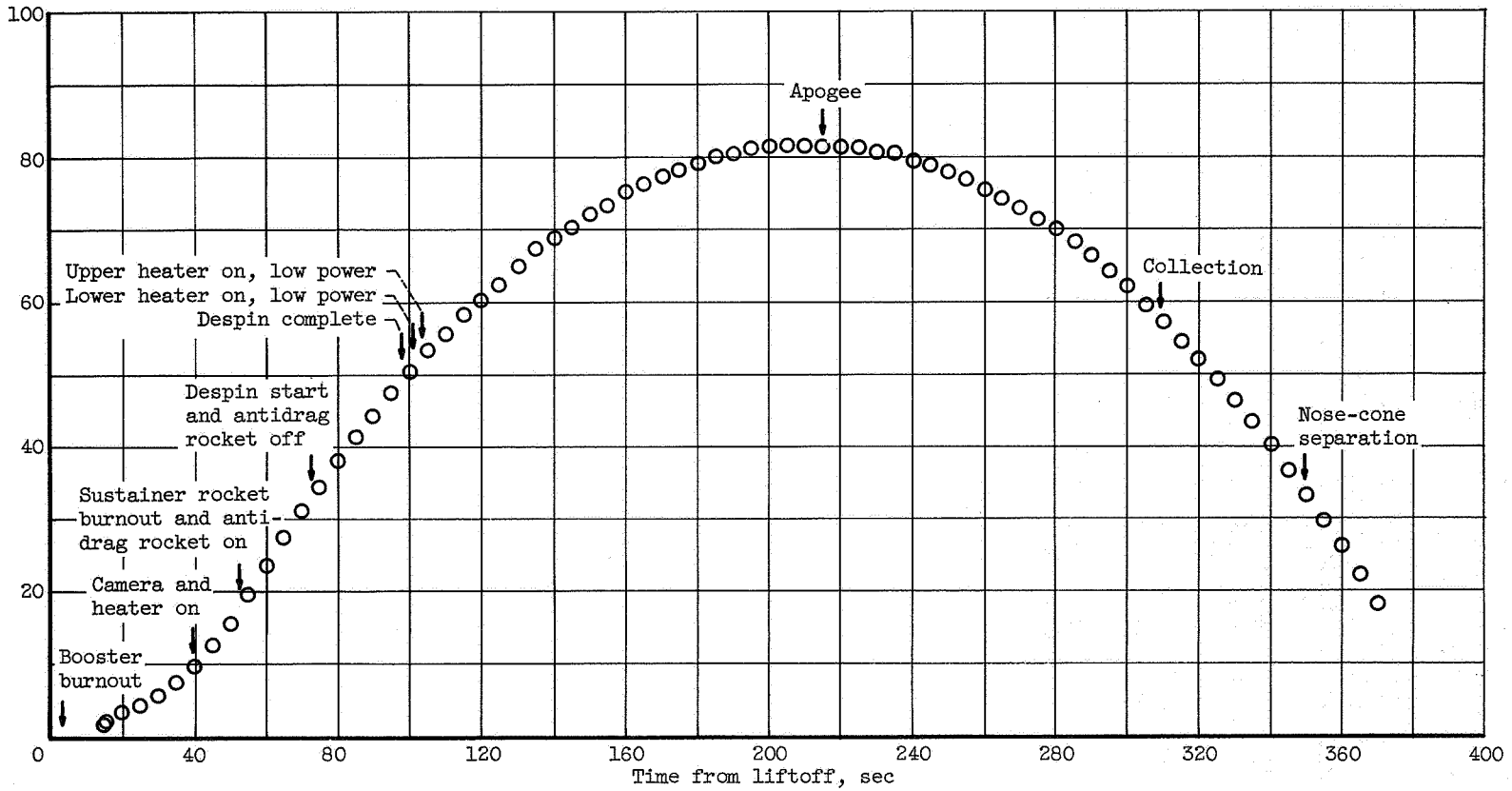

Figure 1. - Trajectory parameter, altitude against time.

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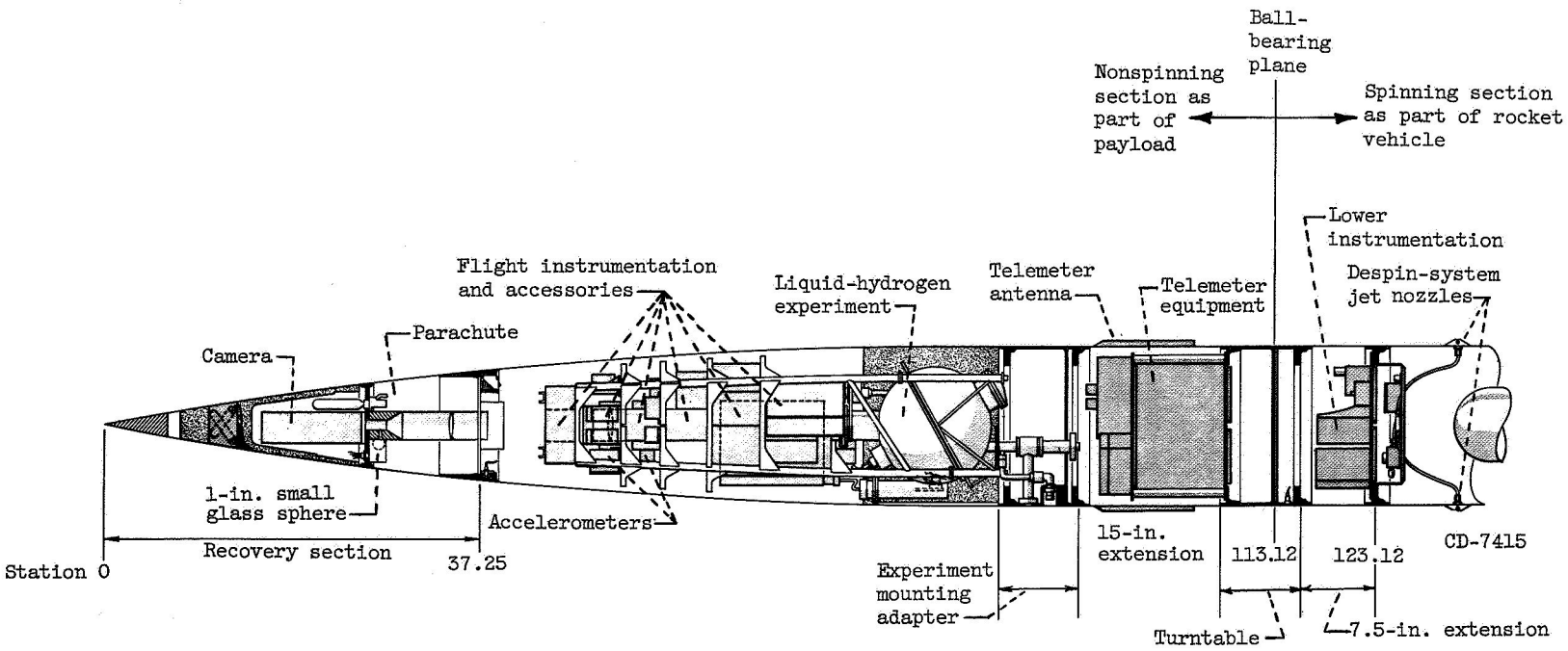
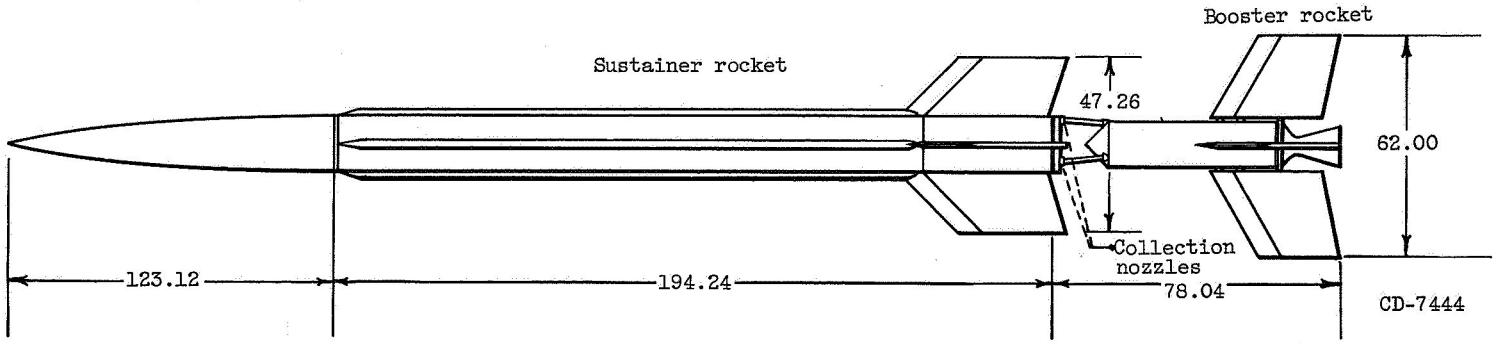


(a) Payload (283.0 lb).



(b) Rocket vehicle, Aerobee 150A.

Figure 2. - Rocket-booster vehicle and payload assembly. (Dimensions in inches.)

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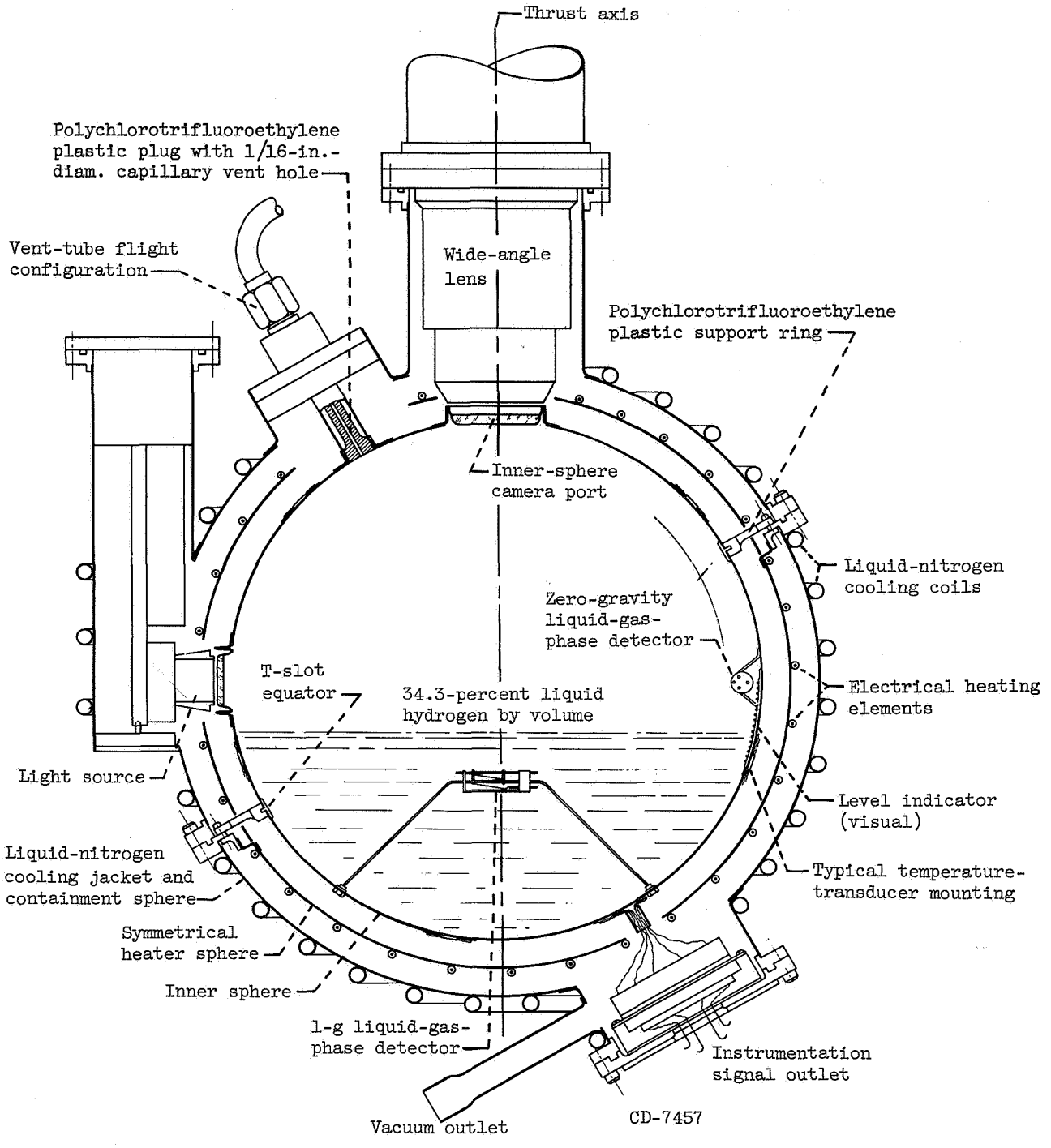
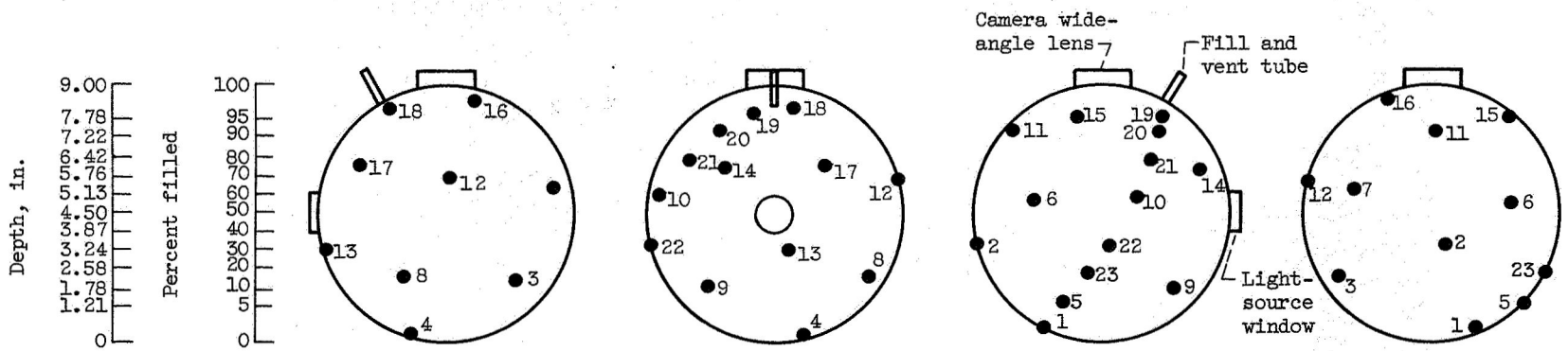
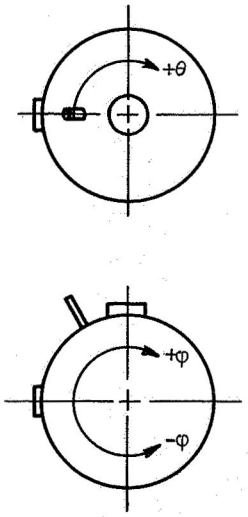


Figure 3. - Zero-gravity heat-transfer apparatus.



(a) General location of temperature transducer (progressively rotated 90°).



Temperature transducer	φ deg	θ deg	Temperature transducer	φ deg	θ deg
1	-60	154	13	-16	354
2	-15	172	14	19	28
3	-32	240	15	57	94
4	-73	330	16	67	257
5	-43	111	17	24	328
6	5	129	18	64	340
7	13	218	19	54	28
8	-28	298	20	40	54
9	-37	46	21	24	68
10	6	78	22	-16	90
11	44	172	23	-27	97
12	18	273			

(b) Spherical-coordinate location.

Figure 4. - Location of temperature transducers on inner sphere of experiment.

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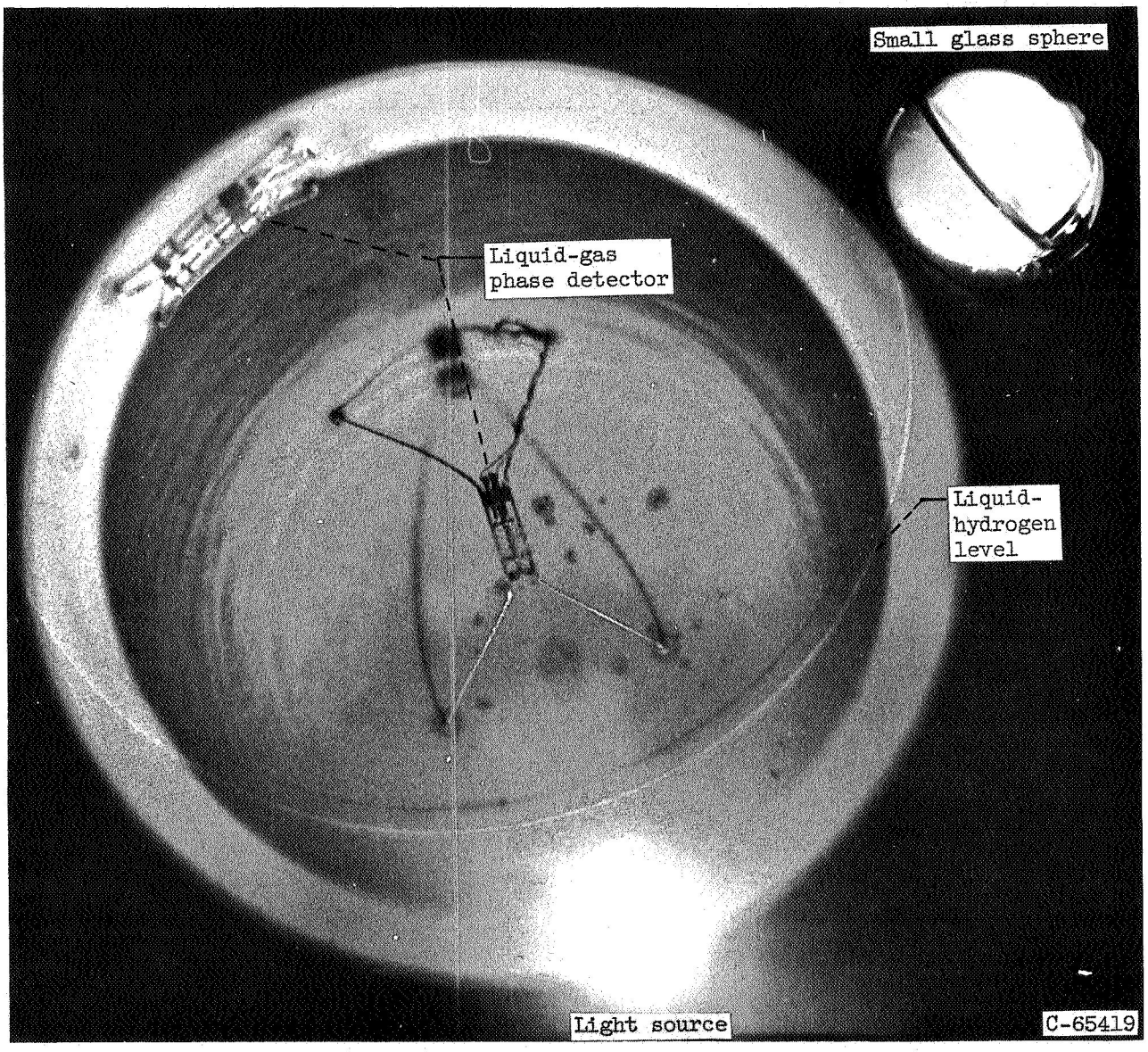

Figure 5. - Interior of liquid-hydrogen sphere prior to launch.

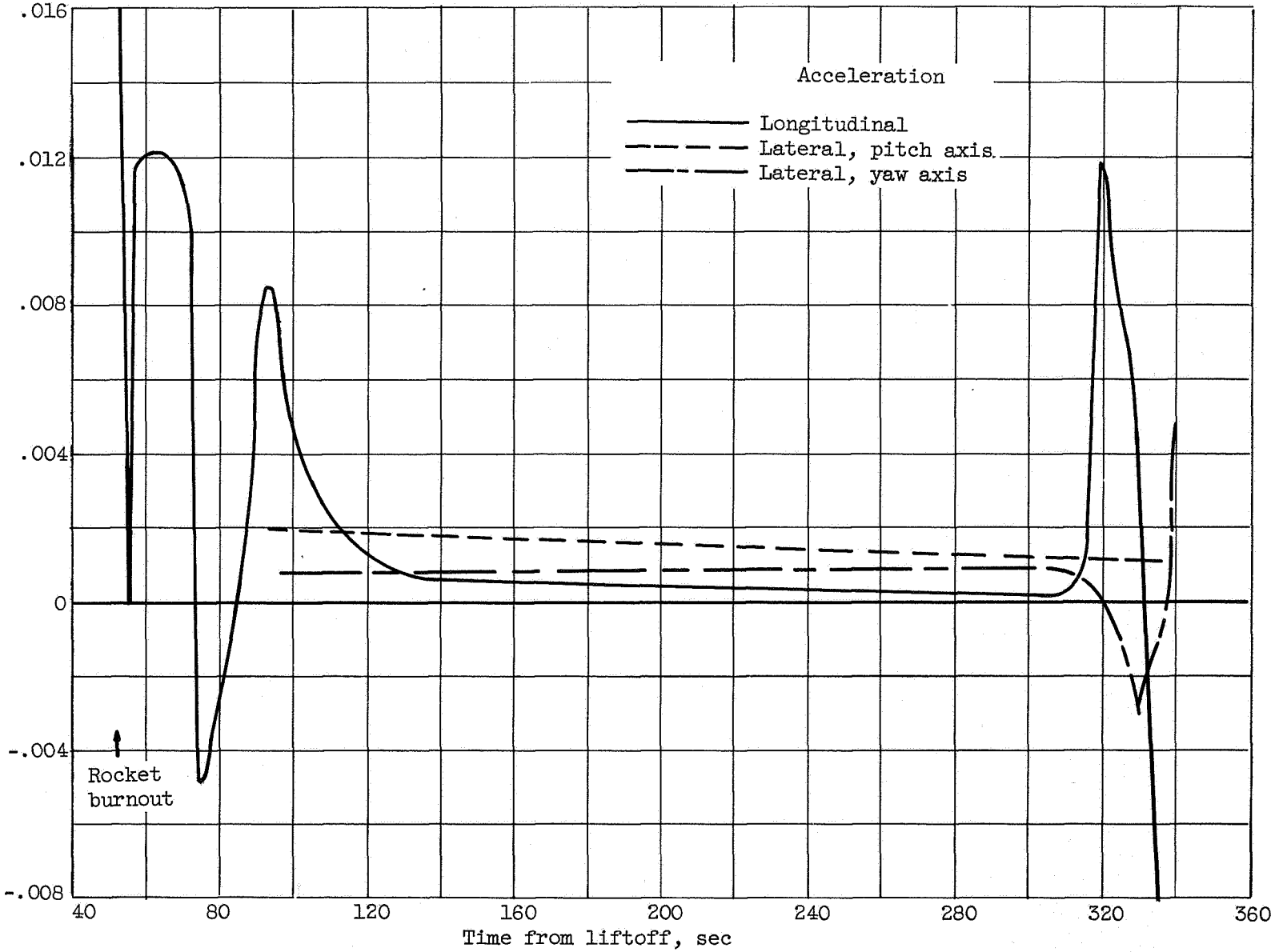

Figure 6. - Acceleration traces obtained during third Aerobee flight.

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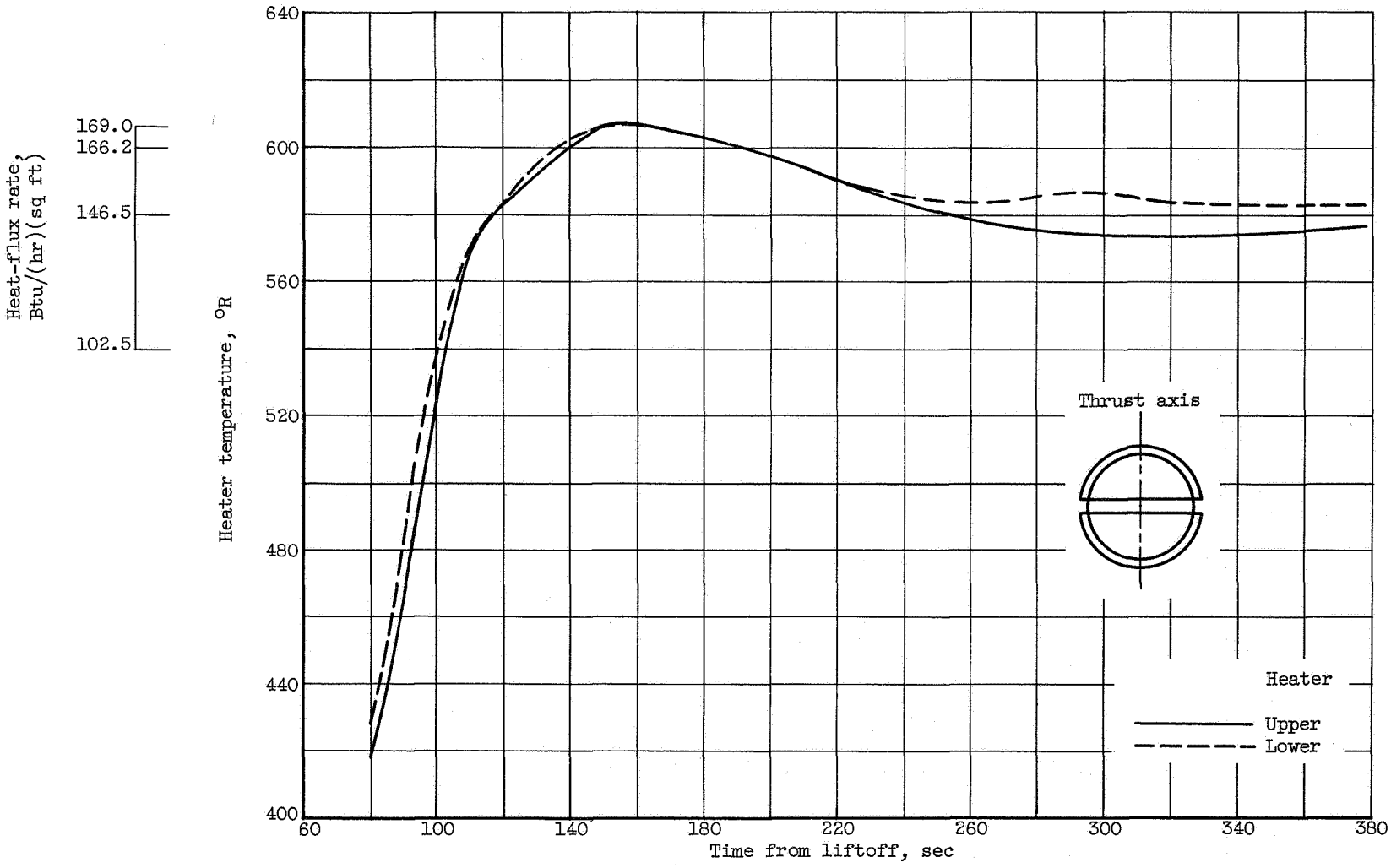

Figure 7. - Time history of upper and lower heater temperatures.

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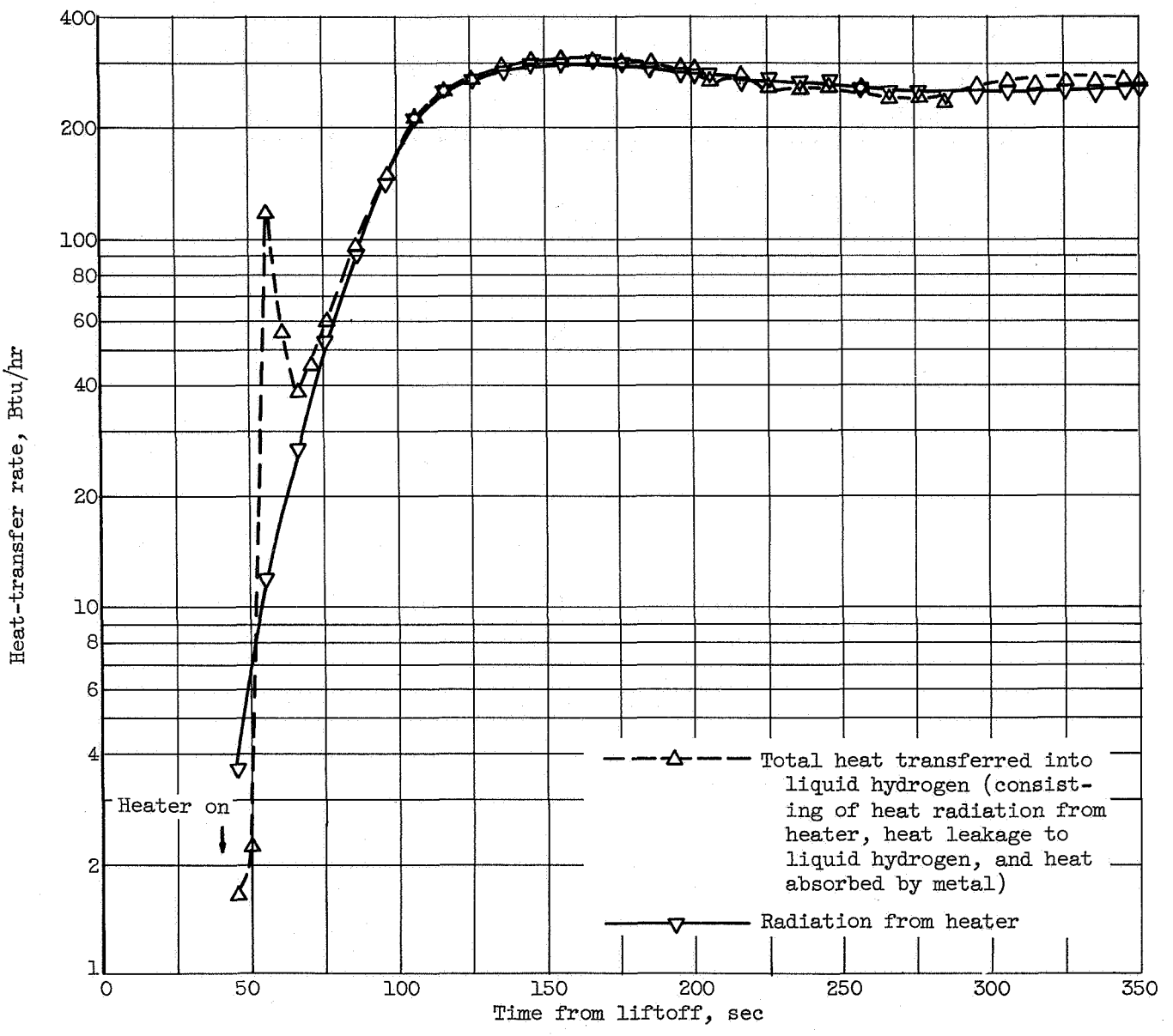
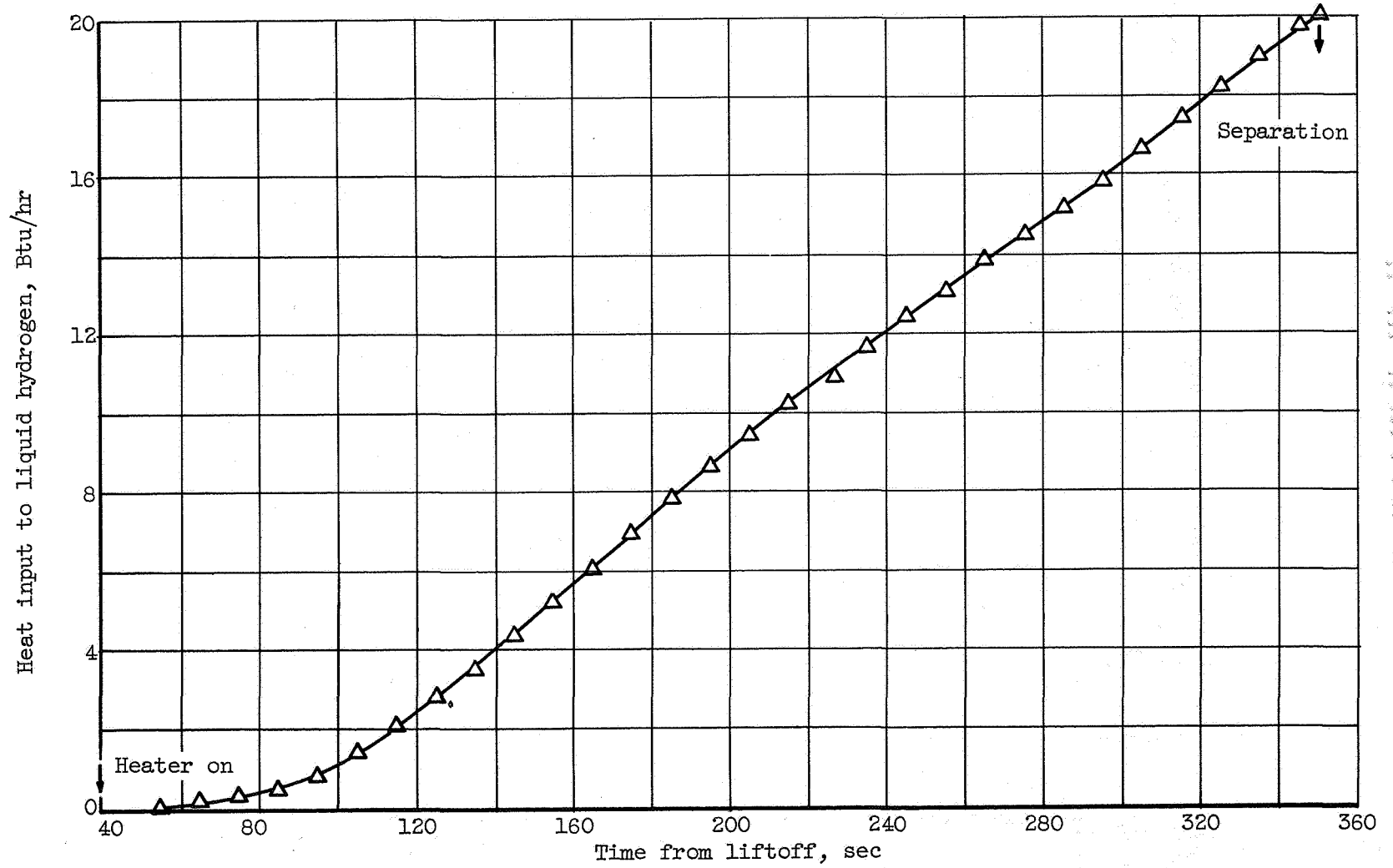


(a) Heat-transfer-rate history.

Figure 8. - Heat transferred to liquid hydrogen.



(b) Heat-input history.

Figure 8. - Concluded. Heat transferred to liquid hydrogen.

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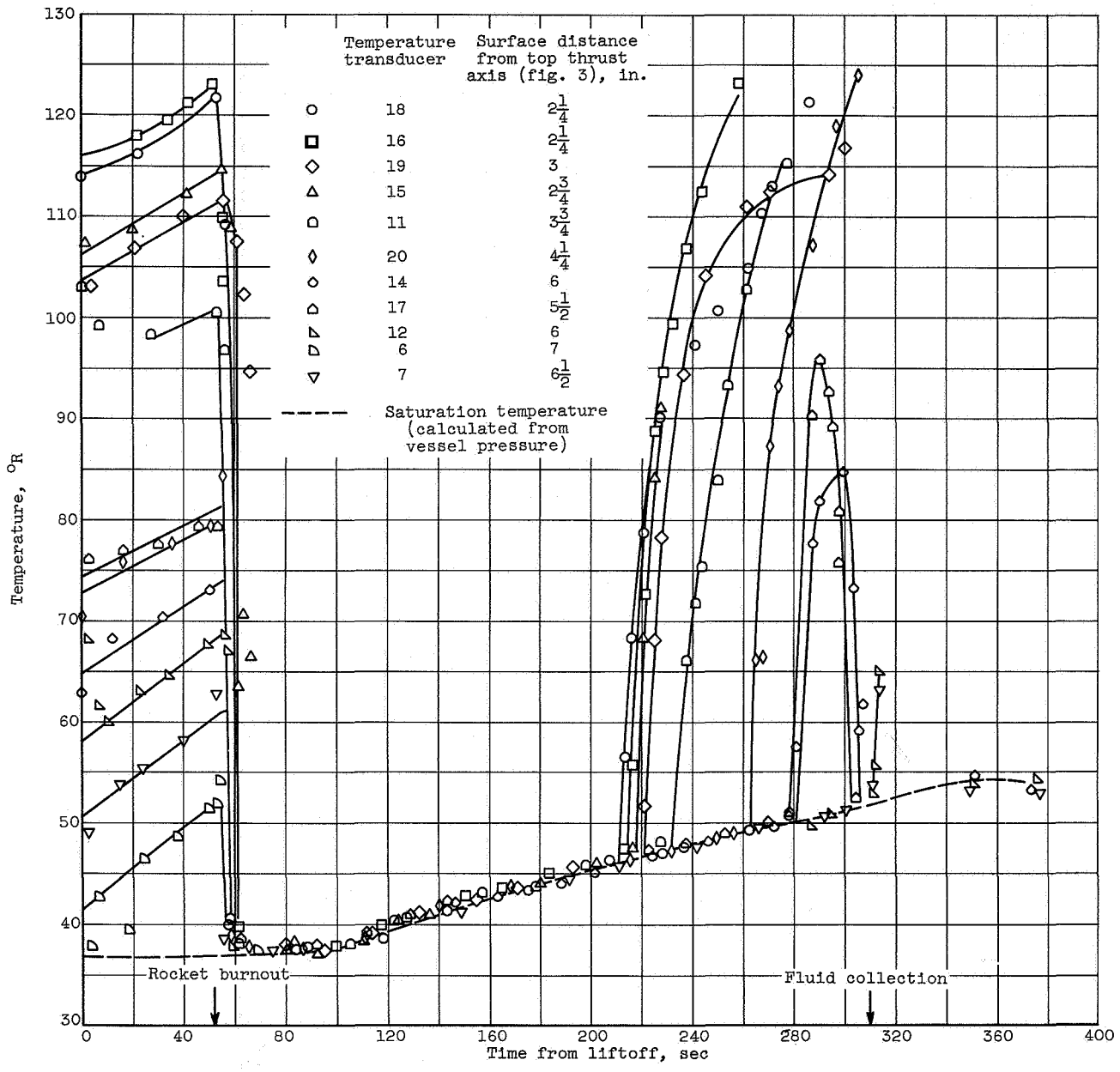
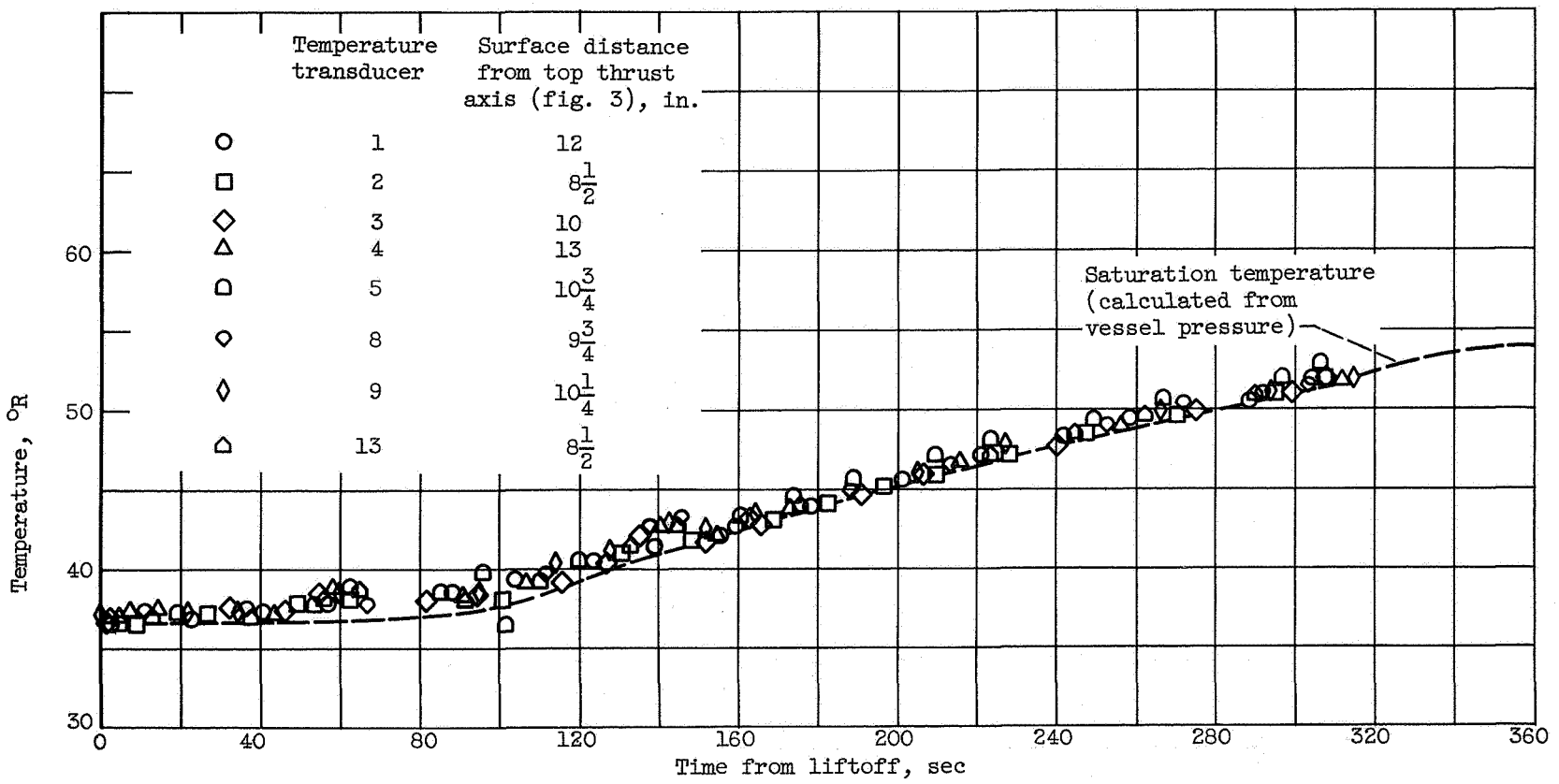


(a) Upper half.

Figure 9. - Vessel-wall-temperature histories for spherical hydrogen tank during weightless test. (Locations of temperature transducers are shown in fig. 4.)



(b) Lower half.

Figure 9. - Concluded. Vessel-wall-temperature histories for spherical hydrogen tank during weightless test. (Locations of transducers are shown in fig. 4.)

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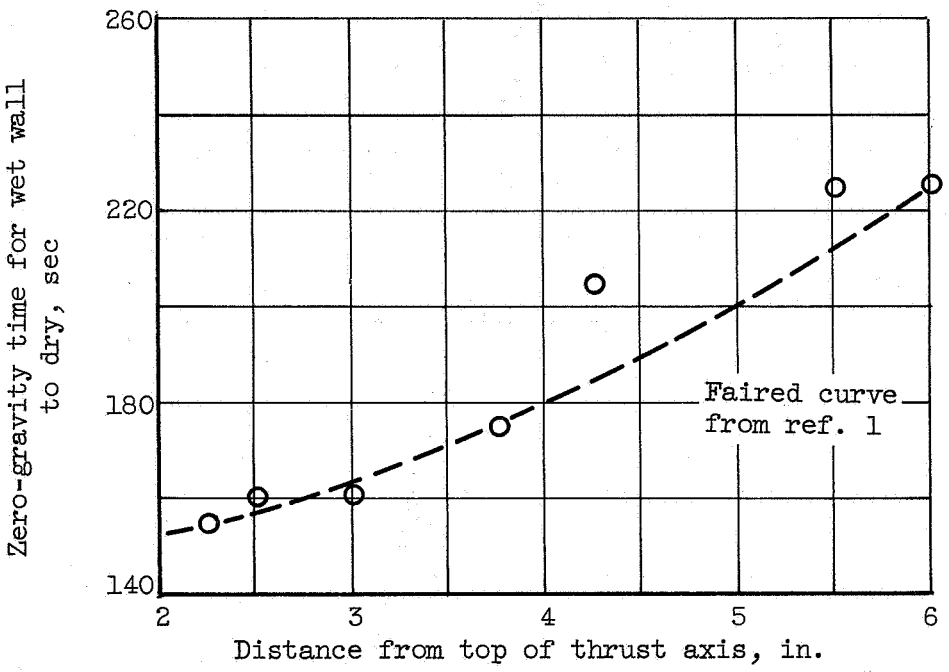

Figure 10. - Zero-gravity time for vessel wall to dry as function of distance from top of thrust axis.

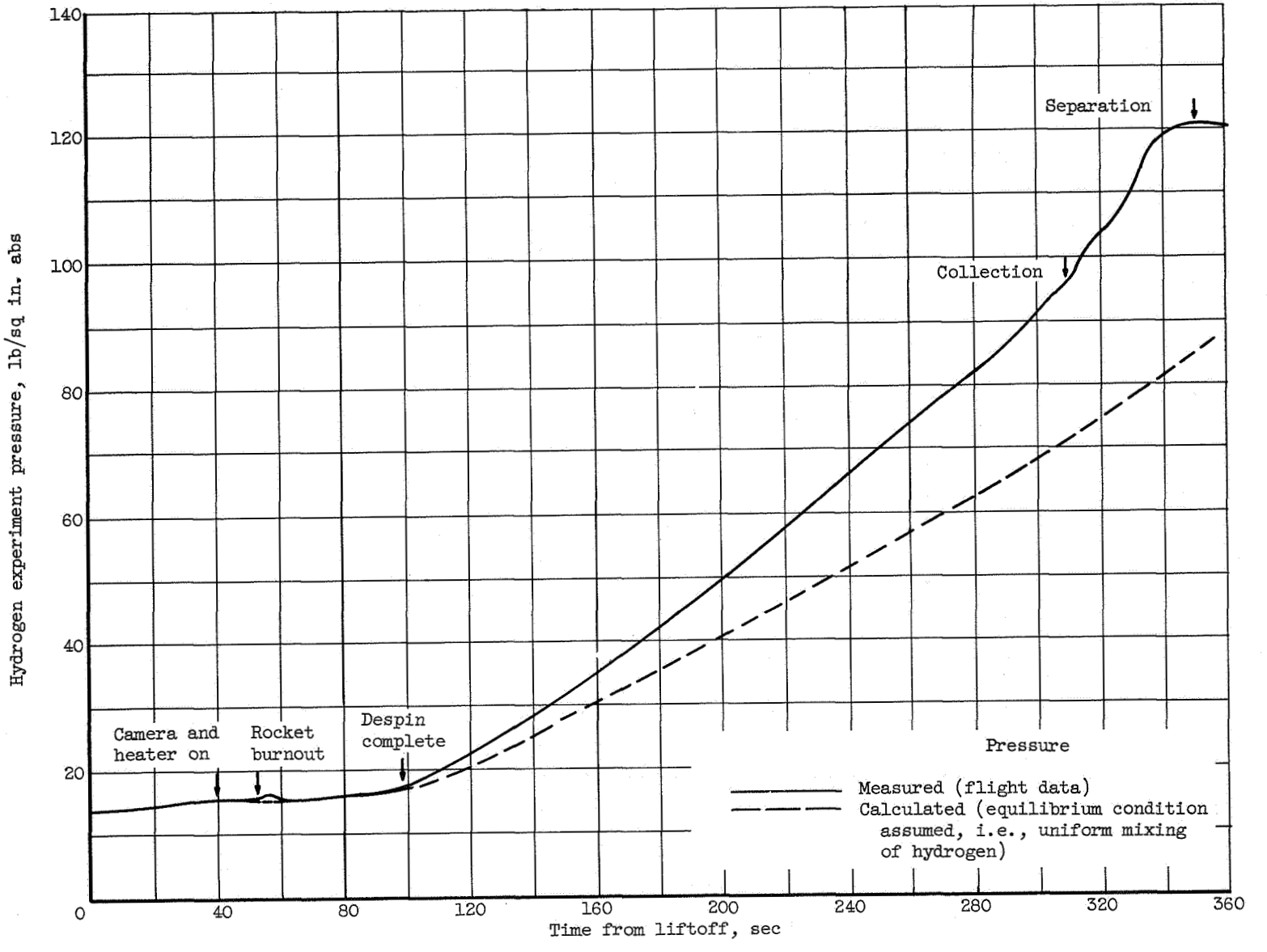

Figure 11. - Pressure history for spherical hydrogen tank during weightless test. (Data for 0 to 50 lb/sq in. were obtained from a 0- to 50-lb/sq in. absolute pressure transducer; data for 50 to 125 lb/sq in. were obtained from a 0- to 200-lb/sq in. absolute pressure transducer; 0 to 50 lb/sq in. data for both pressure transducers were comparable.)

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